

CHARGED HIGGS BOSONS IN THE TRANSITION REGION $M_{H^\pm} \sim m_t$ AT THE LHC

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Abstract

We illustrate preliminary results obtained through Monte Carlo (HERWIG) and detector (ATLFAST) simulations of the $H^\pm \rightarrow \tau^\pm \nu_\tau$ signature of charged Higgs bosons with masses comparable to that of the top quark.

1. THE THRESHOLD REGION

The detection of charged Higgs bosons (H^\pm) would unequivocally imply the existence of physics beyond the Standard Model (SM), since spin-less charged scalar states do not belong to its particle spectrum. Singly charged Higgs bosons appear in any Two-Higgs Doublet Model (2HDM), including a Type-II in presence of minimal Supersymmetry (SUSY), namely, the Minimal Supersymmetric Standard Model (MSSM). Depending on its mass, the machines that are likely to first discover such a state are Tevatron $p\bar{p}$ ($\sqrt{s} = 2$ TeV) and the LHC ($\sqrt{s} = 14$ TeV). Current limits on the charged Higgs boson mass are set by LEP at about 80 GeV. At the Tevatron a charged Higgs boson could be discovered for masses up to $m_t - m_b$, whereas the LHC has a reach up to the TeV scale, if $\tan \beta$ is favourable (i.e., either large or small).

For the LHC, the ATLAS discovery potential of H^\pm bosons in a general Type-II 2HDM or MSSM (prior to the results of this study) is visualised in the left-hand side of Fig. 1. (A similar CMS plot, also including neutral Higgs states, is given for comparison.) The existence of a gap in coverage for $M_{H^\pm} \approx m_t$ was already denounced in Refs. [1, 2] as being due to the fact that Monte Carlo (MC) simulations of H^\pm production for $M_{H^\pm} \sim m_t$ were flawed by a wrong choice of the hard scattering process. In fact, for $M_{H^\pm} < m_t$, the estimates in both plots in Fig. 1 were made by assuming as main production mode of H^\pm scalars the decay of top (anti)quarks produced via QCD in the annihilation of gluon-gluon and quark-antiquark pairs (hence – by definition – the attainable Higgs mass is strictly confined to the region $M_{H^\pm} \leq m_t - m_b$). This should not be surprising (the problem was also encountered by CMS, see right-hand side of Fig. 1), since standard MC programs, such as PYTHIA and HERWIG [3, 4], have historically accounted for this process through the usual procedure of factorising the production mode, $gg, q\bar{q} \rightarrow t\bar{t}$, times the decay one, $\bar{t} \rightarrow \bar{b}H^-$, in the so-called Narrow Width Approximation (NWA) [5]. This description fails to correctly account for the production phenomenology of charged Higgs bosons when their mass approaches or indeed exceeds that of the top-quark (i.e., falls in the so called ‘threshold region’). This is evident from the left plot in Fig. 2. (The problem also occurs at Tevatron, see right plot therein and Refs. [5, 6].) As remarked in Ref. [5], the use of the $2 \rightarrow 3$ hard scattering process $gg, q\bar{q} \rightarrow t\bar{b}H^-$ [7]–[11], in place of the ‘factorisation’ procedure in NWA, is mandatory in the threshold region, as the former correctly keeps into account both effects of the finite width of the top quark and the presence of other H^\pm production mechanisms, such as Higgs-strahlung and $b\bar{t} \rightarrow H^-$ fusion (and relative interferences). The differences seen between the two descriptions in Fig. 2 are independent of $\tan \beta$ and also survive in, e.g., p_T and η spectra [5].

One more remark is in order, concerning the LHC plot in Fig. 2. In fact, at the CERN hadron collider, the above $2 \rightarrow 3$ reaction is dominated by the gg -initiated subprocesses, rather than by $q\bar{q}$ -annihilation, as is the case at the Tevatron. This means that a potential problem of double counting arises in the simulation of $tH^-X + \text{c.c.}$ events at the LHC, if one considers that Higgs-strahlung can also be emulated through the $2 \rightarrow 2$ process $bg \rightarrow tH^- + \text{c.c.}$, as was done in assessing the ATLAS (and CMS) discovery reaches in the $H^\pm \rightarrow t\bar{b}$ and $H^\pm \rightarrow \tau^\pm \nu_\tau$ channels for $M_{H^\pm} > m_t$ (see Refs. [12, 16] for reviews). The difference between the two approaches is well understood, and prescriptions exist for combining the two, either through the subtraction of a common logarithmic term [9, 17] or by means of a cut in phase space [11].

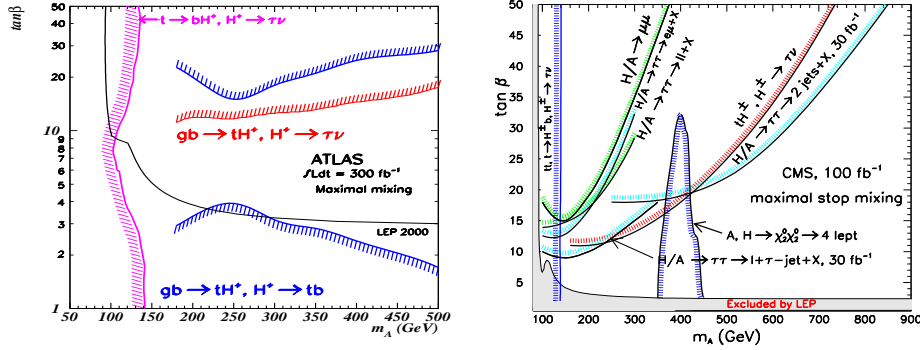


Fig. 1: The ATLAS 5- σ discovery contours of 2HDM charged Higgs bosons for 300 fb^{-1} of luminosity, only including the reach of SM decay modes (left plot). The CMS 5- σ discovery contours of MSSM Higgs bosons for 100 fb^{-1} of luminosity, also including the reach of $H, A \rightarrow \chi_2^0 \chi_2^0 \rightarrow 4l^\pm$ decays, assuming $M_1 = 90 \text{ GeV}$, $M_2 = 180 \text{ GeV}$, $\mu = 500 \text{ GeV}$, $M_{\tilde{t}} = 250 \text{ GeV}$, $M_{\tilde{q},\tilde{g}} = 1000 \text{ GeV}$ (right plot).

If one then looks at the most promising (and cleanest) charged Higgs boson decay channel, i.e., $H^\pm \rightarrow \tau^\pm \nu_\tau$ [18], while using the $gg, q\bar{q} \rightarrow t\bar{b}H^- + \text{c.c.}$ description and reconstructing the accompanying top quark hadronically, the prospects of H^\pm detection should improve significantly for M_{H^\pm} values close to m_t , eventually leading to the closure of the mentioned gap. The $2 \rightarrow 3$ description of the H^\pm production dynamics (as well as the spin correlations in τ -decays usually exploited in the ATLAS $H^\pm \rightarrow \tau^\pm \nu_\tau$ analysis) have been made available in version 6.4 [19] of the HERWIG event generator (the latter also through an interface to TAUOLA [20]), so that detailed simulations of H^\pm signatures at both the Tevatron and the LHC are now possible for the threshold region, including fragmentation/hadronisation and detector effects. In the next section we will discuss the details of an ATLAS analysis based on such tools that has lead to the closure of the mentioned gap through the discussed charged Higgs decay channel. This analysis was initiated in the context of the 2003 Les Houches workshop.

2. ANALYSIS

The signal $gg \rightarrow t\bar{b}H^\pm \rightarrow jjb\tau\nu$ and the major backgrounds, $gg \rightarrow t\bar{t} \rightarrow jjb\tau\nu b$ and $q\bar{q}, qg, \bar{q}g \rightarrow W + \text{jets}$, are generated with HERWIG v6.4 in the default implementation except for CTEQ5L [21] Parton Distribution Functions (PDFs). The detector is simulated with ATLFAST [22]. The TAUOLA package [20] is used for the polarisation of the τ -lepton. The selection of the final state requires a multi-jet trigger with a τ -trigger:

- (1) We search for one hadronic τ -jet, two b -tagged jets and at least two light-jets, all with $p_T > 30 \text{ GeV}$. Furthermore, the τ -jet and the b -tagged jets are required to be within the

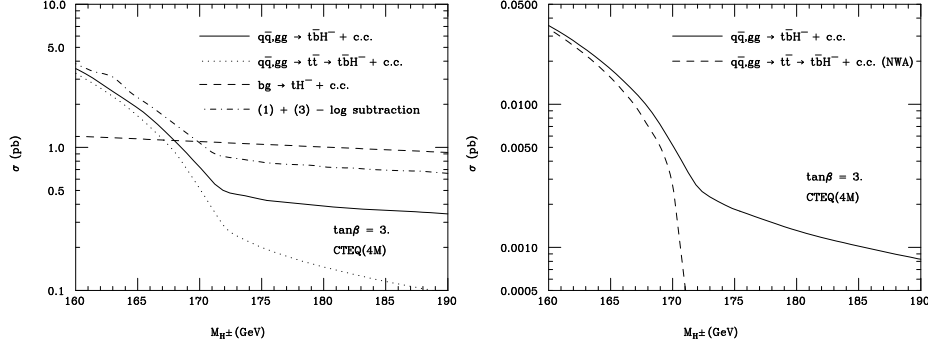


Fig. 2: Cross section for $gg, q\bar{q} \rightarrow t\bar{b}H^-$, $gg, q\bar{q} \rightarrow t\bar{t} \rightarrow t\bar{b}H^-$ with finite top quark width, $bg \rightarrow tH^-$ and the combination of the first and the last, at the LHC with $\sqrt{s} = 14$ TeV (left plot). Cross section for $gg, q\bar{q} \rightarrow t\bar{b}H^-$ and $gg, q\bar{q} \rightarrow t\bar{t} \rightarrow t\bar{b}H^-$ in NWA, at the Tevatron with $\sqrt{s} = 2$ TeV (right plot). Rates are function of M_{H^\pm} for a representative value of $\tan\beta$.

tracking range of the ATLAS Inner Detector, $|\eta| < 2.5$. We assume a τ -tagging efficiency of 30% and a b -tagging efficiency of 60%(50%) at low(high) luminosity. The efficiency of this selection is at the level of 1.31% for the signal (e.g., at $M_{H^\pm} = 170$ GeV), 1.25% for $gg \rightarrow t\bar{t} \rightarrow jjb\tau\nu b$ events and $(0.36 \times 10^{-3})\%$ for W^\pm +jets events.

- (2) We reconstruct the invariant masses of pairs of light-jets, m_{jj} , and keep those consistent with the W^\pm mass: $|m_{jj} - M_W| < 25$ GeV. The associated top-quark is then reconstructed requiring $|m_{jjb} - m_t| < 25$ GeV. For the signal with a charged Higgs mass of 170 GeV, 0.68% of signal events pass this selection criteria compared to 0.73% and $(0.45 \times 10^{-6})\%$ for the $t\bar{t}$ and W^\pm +jets backgrounds, respectively.
- (3) We require that the transverse momentum of the τ -jet be greater than 100 GeV, the transverse missing momentum be greater than 100 GeV and the azimuthal opening angle between the τ -jet and the missing momentum vector be greater than one radian. Indeed, in the signal, the τ -lepton originates from a scalar particle (H^\pm) whereas in the background the τ -lepton comes from the decay of a vector particle (W^\pm). This difference reflects in the polarisation state of the τ and leads to harder τ -jets in the signal compared to the backgrounds [12]–[15]. Furthermore, to satisfy the large cut on the transverse missing momentum and because the charged Higgs is heavier than the W^\pm -boson, a much larger boost is required from the W^\pm - in the background than from the H^\pm -boson in the signal. As a result, the spectra of the azimuthal opening angle between the τ -jet and the missing transverse momentum are different for signals and backgrounds, as shown in Fig. 3 (left plot).

Although the full invariant mass of the $H^\pm \rightarrow \tau\nu$ system cannot be reconstructed because of the neutrino in the final state, the transverse mass (which is kinematically constrained to be below the W^\pm -mass in the backgrounds and below the H^\pm -mass in the signal)

$$m_T = \sqrt{2p_T^{\tau\text{-jet}}p_T[1 - \cos(\Delta\phi)]} \quad (1)$$

combines the benefits of both the polarisation effects and the kinematic boost, thus providing a good discriminating observable, as shown in Fig. 3 (right plot). (The residual background under the signal is due to the experimental E_T^{miss} resolution.)

- (4) We also apply a combination of other cuts on: the invariant mass and the azimuthal opening angle of the τb -jet system, where b -jet is here the remaining one after the reconstruc-

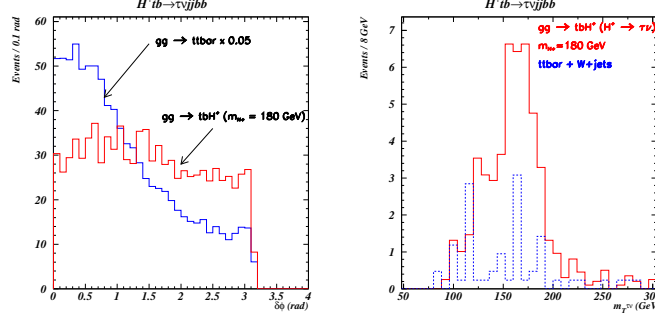


Fig. 3: The plot on the left shows the azimuthal opening angle between the τ -jet and the transverse missing momentum. It peaks forward in the background and more and more backward in the signal, as the charged Higgs mass increases. The right plot shows the reconstructed transverse mass for a 180 GeV Higgs. (Both plots are shown for an integrated luminosity of 30 fb^{-1} .)

Table 1: Sensitivity of the ATLAS detector to the observation of charged Higgs bosons through $H^\pm \rightarrow \tau\nu$ decays in the transition region, for an integrated luminosity of 30 fb^{-1} and $\tan\beta = 50$.

M_{H^\pm} (GeV)	160	170	180	190
Signal (S)	35	46	50	35
Backgrounds (B)	13	13	13	13
S/B	2.7	3.5	3.8	2.7
S/\sqrt{B}	9.7	12.8	13.9	9.7
Poisson Significance	7.3	9.1	9.8	7.3
Poisson Significance+5% syst.	7.1	8.9	9.5	7.1

tion of the top quark ($m_{\tau b\text{-jet}} > 100 \text{ GeV}$ and $\Delta\Phi(\tau\text{-jet}, b\text{-jet}) > 1.25$ radians); the invariant mass of the $b\bar{b}$ pair ($m_{b\bar{b}\text{-jet}} > 225 \text{ GeV}$) and the transverse mass of the τb -jet system ($p_T^{\tau b\text{-jet}} > 190 \text{ GeV}$). The cumulative effect of these cuts is the reduction of the W^\pm +jets background by more than one order of magnitude, while the signal ($M_{H^\pm} = 170 \text{ GeV}$) and the $t\bar{t}$ background are suppressed by only a factor of two.

- (5) Finally, we require $m_T > 100 \text{ GeV}$ for the calculation of the signal-to-background ratios and the signal significances in Tab. 1. This cut is very efficient against the $t\bar{t}$ noise (the efficiency is 0.06% for a $M_{H^\pm} = 170 \text{ GeV}$ Higgs signal, 1.9×10^{-3} and 0.42×10^{-6} for the $t\bar{t}$ and the W^\pm +jets backgrounds, respectively).

3. RESULTS

The discovery contour in the transition region resulting from this new analysis is shown in Fig. 4. Notice that, at lower masses, the signal reconstruction efficiency decreases (although the rate is higher), thus explaining the upward turn of the discovery reach.

Before closing, some additional information is in order regarding the interplay between the new curve and the two old ones. In fact, recall that above the top-quark mass, the $2 \rightarrow 2$ process, $bg \rightarrow tH^\pm$, with $H^\pm \rightarrow \tau\nu$, was used while below it the charged Higgs was searched for in top-quark decays, $t \rightarrow bH^\pm$, counting the excess of τ -leptons over the SM expectations. Furthermore, in the analysis above the top-quark mass, CTEQ2L PDFs [21] were used and the charged Higgs production cross sections were obtained from another generator, PYTHIA

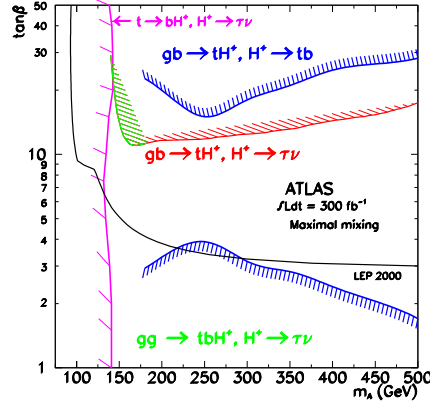


Fig. 4: The new ATLAS discovery potential for charged Higgs bosons. The results of the current analysis are shown in green.

v5.7. These differences complicate the matching of the various contours at their boundaries, especially between the transition region and the high mass region ($M_{H^\pm} > m_t$). In the result shown, the normalisation cross sections for the transition region were matched to the PYTHIA v5.7 numbers above m_t , for consistency with the previous analysis of the high mass region [12]. A second stage of this analysis is currently underway to update all the discovery contours by adopting the same $2 \rightarrow 3$ production process throughout.

4. CONCLUSIONS

Meanwhile, as *ad interim* conclusion, we would like to claim that the LHC discovery potential of charged Higgs bosons has been extended further by our preliminary analysis.

ACKNOWLEDGEMENTS

We would like to thank the 2003 Les Houches workshop organisers for their kind invitation. SM is grateful to The Royal Society (London, UK) for a Conference Grant.

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